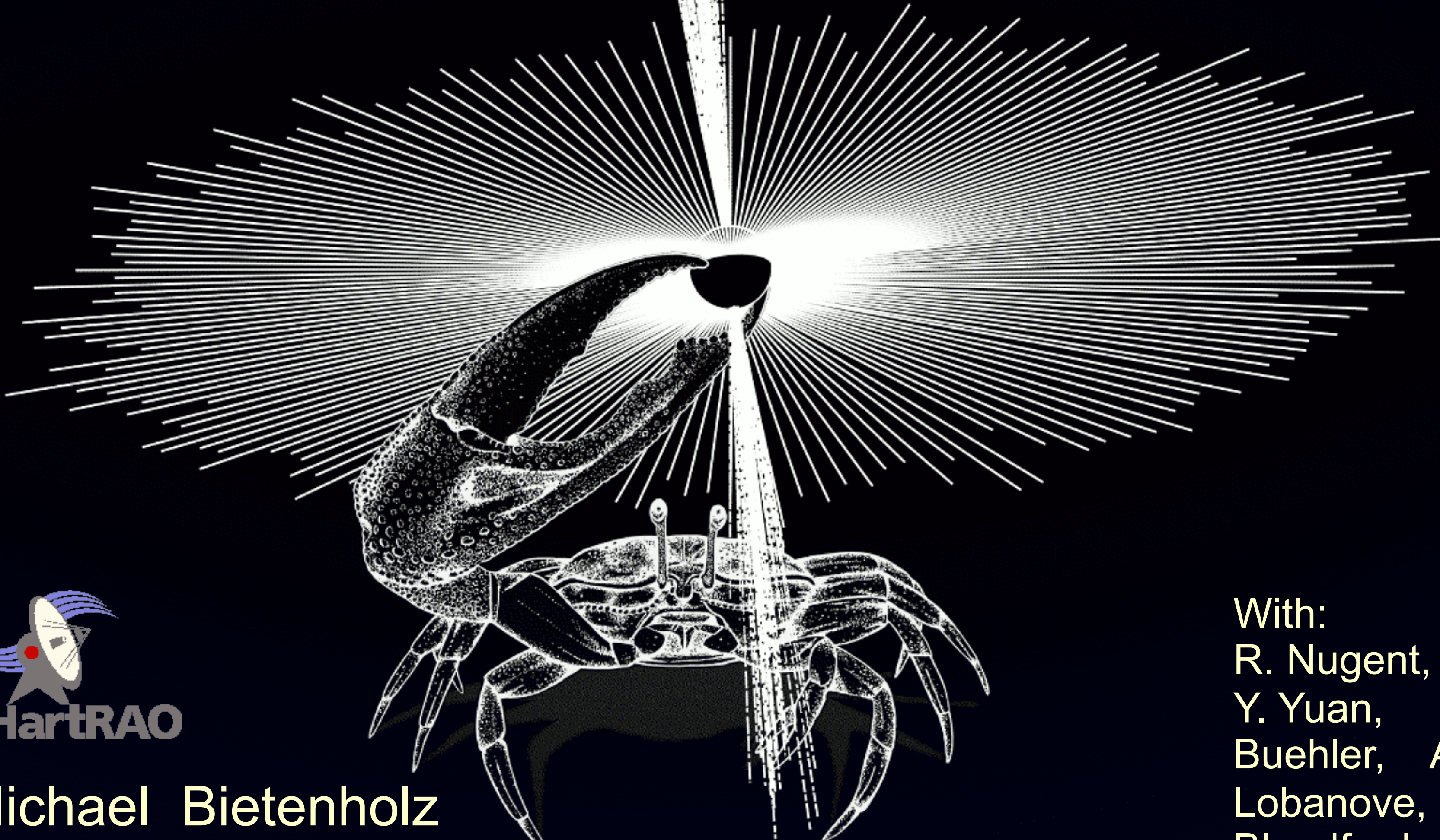
New Radio and Optical Expansion Rate Measurements of the Crab Nebula



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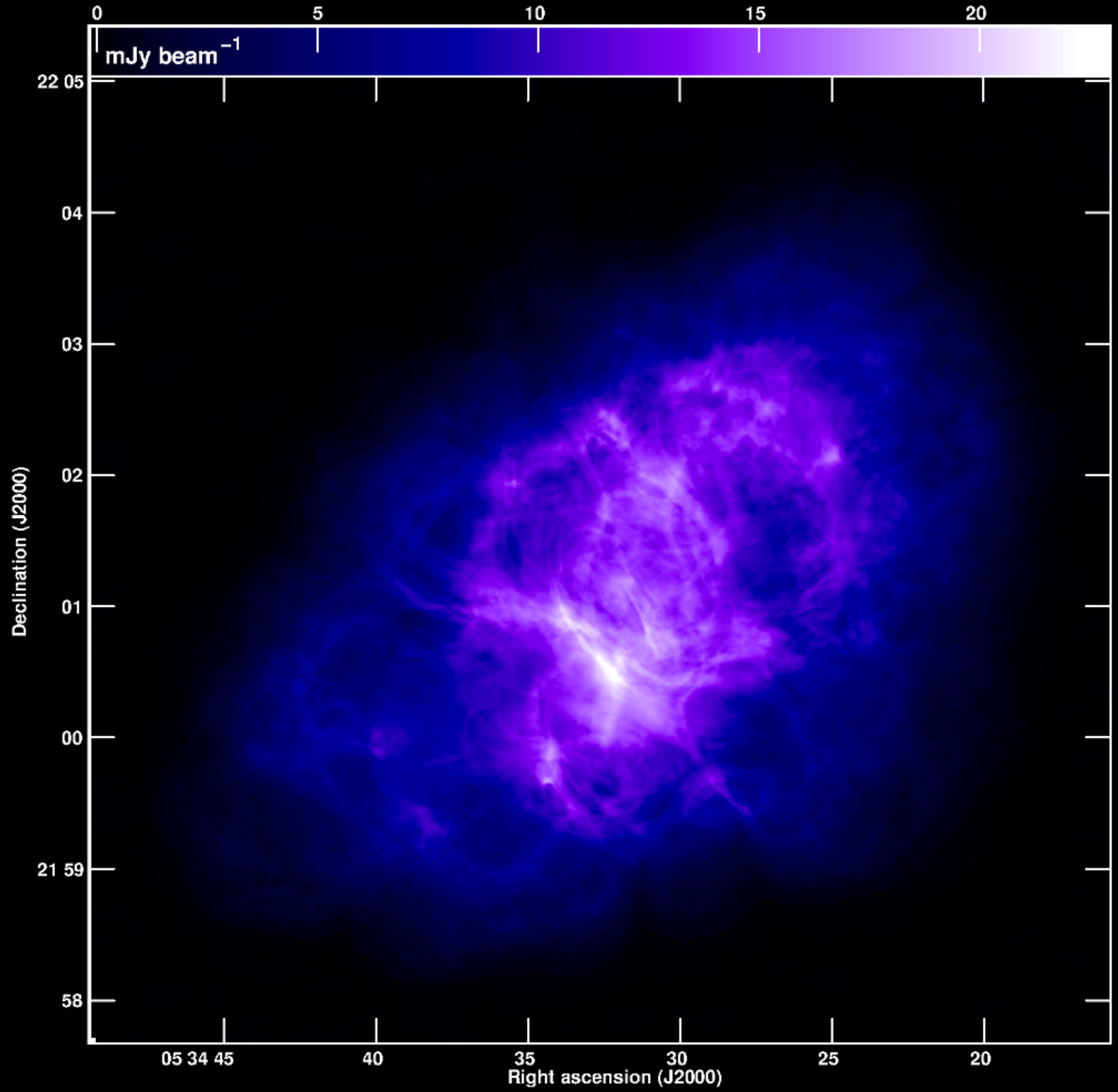
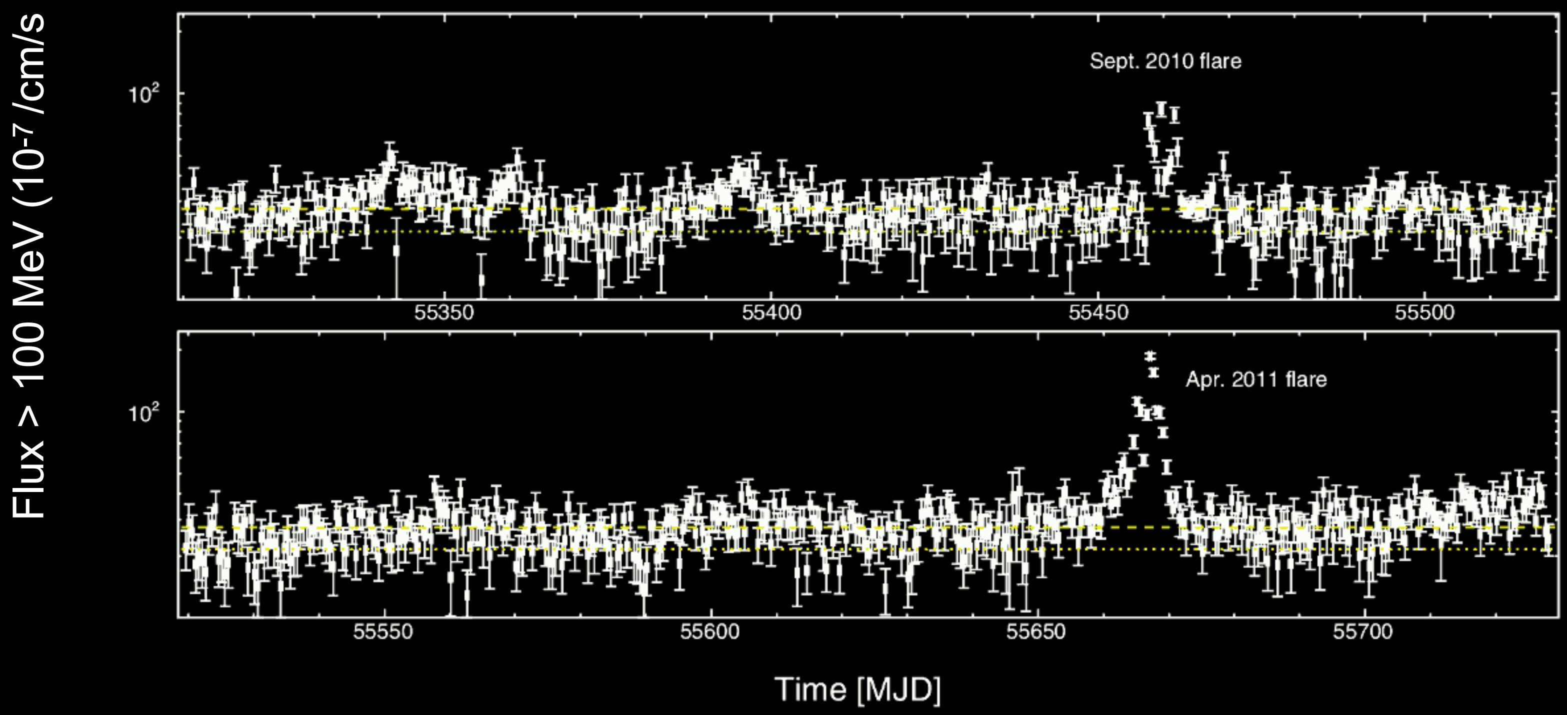


- Crab Nebula
- 2012 Aug 26
- JVLA 5.5 GHz
- peak 22.9 mJy/beam
- rms back-ground 28 μJy/beam
- resolution 1.0" FWHM

Gamma-Ray Flares in the Crab

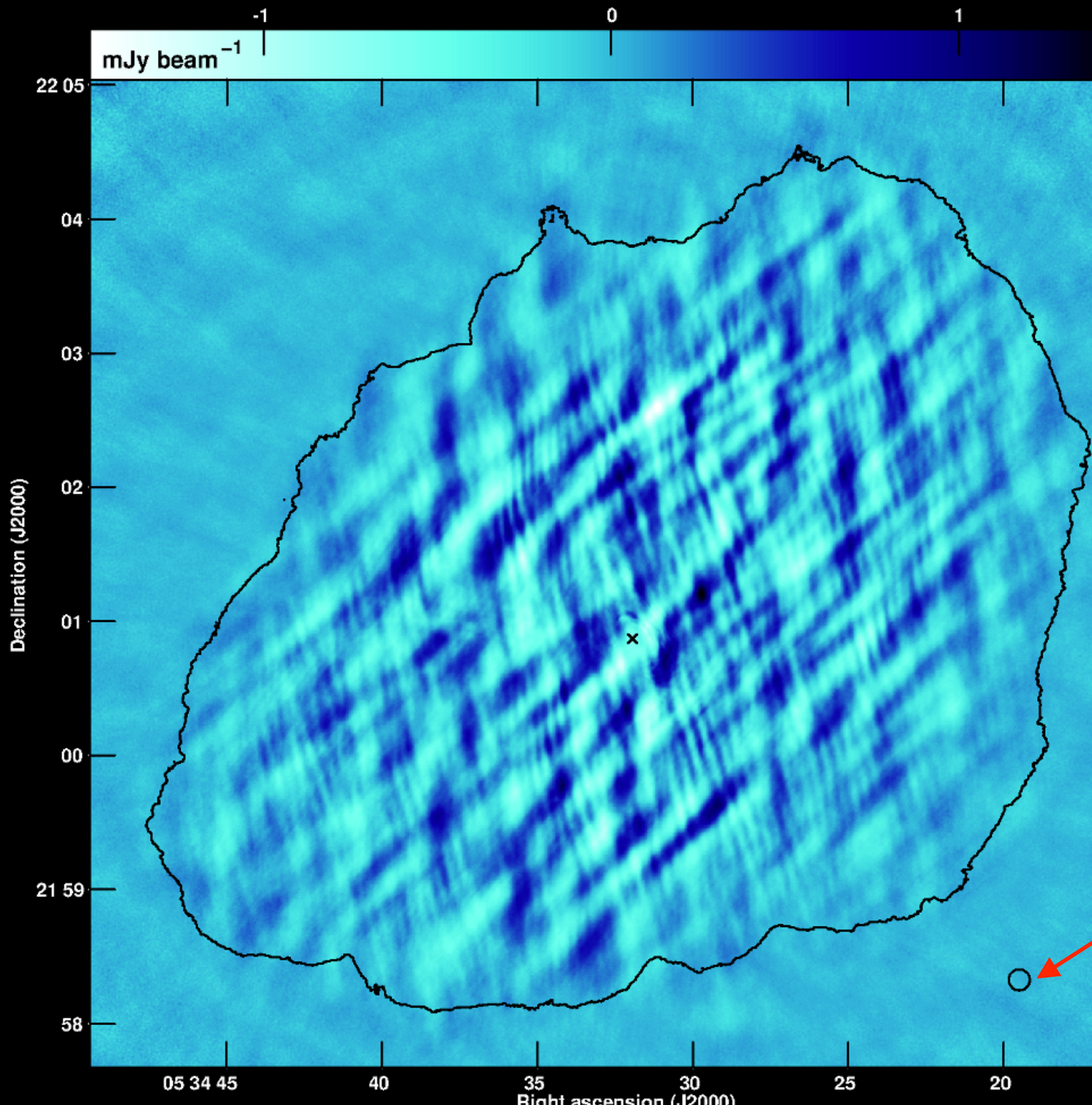


Examples of flares from *Fermi* observations. Fluxes shown are the total of that from the inverse-Compton nebula and from the pulsar. The dashed yellow line shows average value.

Buehler et al, 2012

Using Radio to Localize the Gamma-Ray Flares

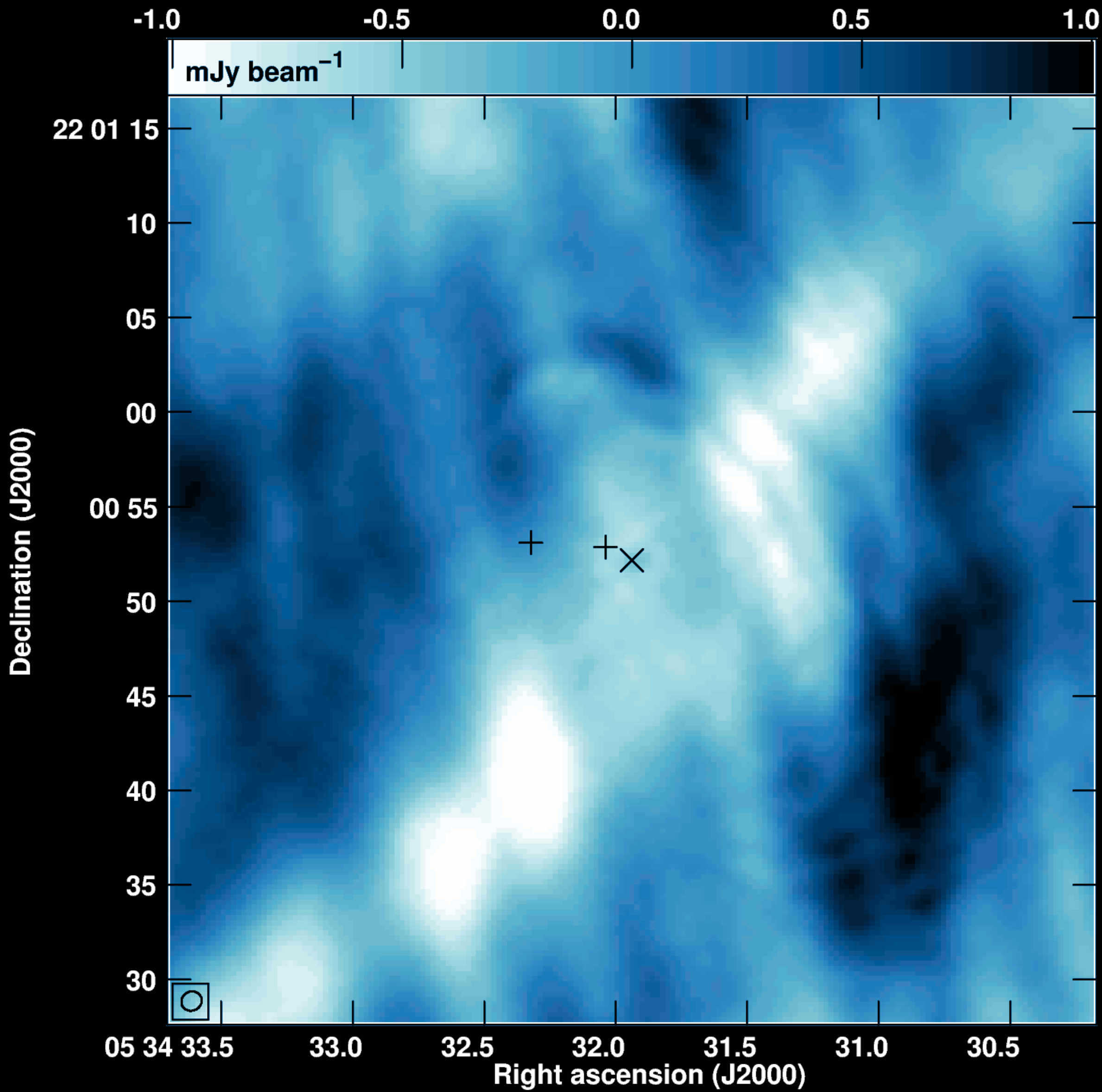
- Radio emission is often associated with gamma-ray emission
- Arcsec resolution easily obtainable in the radio
- A new gamma-ray flare was detected 2012 July 3 (Ojha et al 2012)
- We obtained Jansky VLA observations of the Crab 2012 Aug. 20 and 26, or 49 and 55 days after the onset of the flare.
- We observed in the B array configuration at 5 GHz with a total time of 5 h per session
- Earlier attempts to detect radio emission after a gamma-ray flare by Lobanov et al 2011 and Weisskopf et al 2013



- Difference between two epochs 6 days apart (5.5 GHz)
- contour is 1% contour from 2012 Aug 26
- Brightness of any component associated with the gamma-ray flare is < 2 mJy//bm

The circle indicates the diameter corresponding to *c* since the gamma-ray flare

Difference Image: Detail

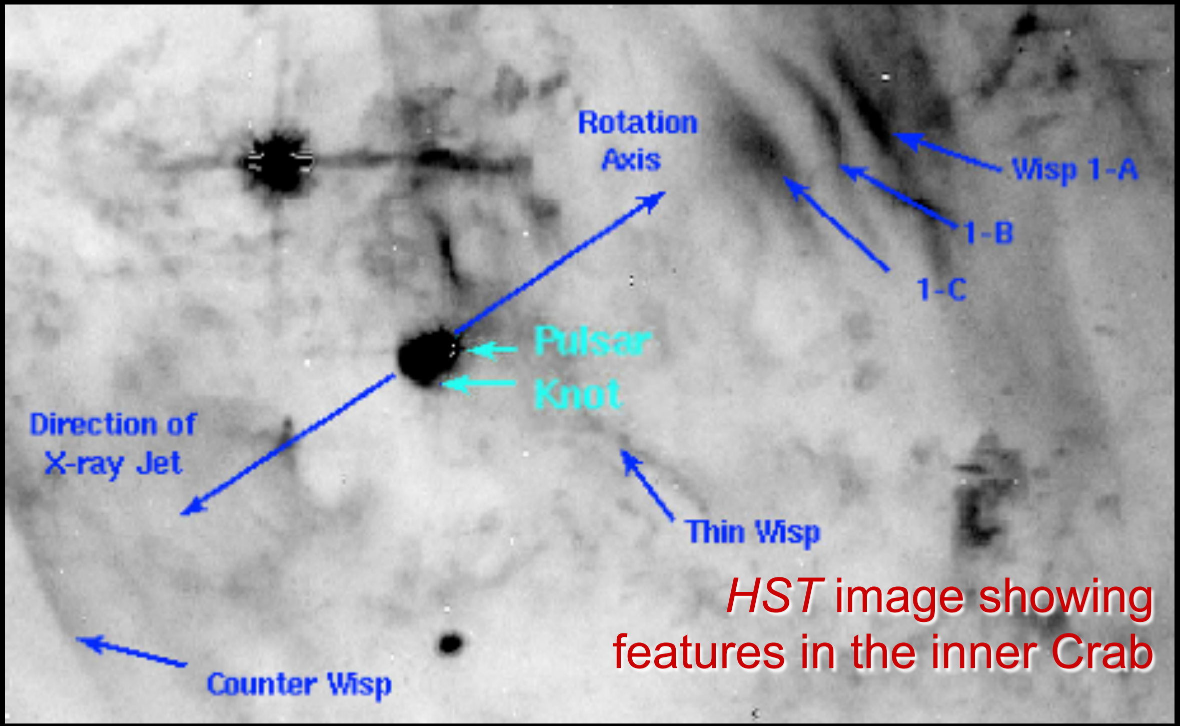


- Difference between two epochs 6 days apart (5.5 GHz)
- high-pass filtered 37"
- resolution 0.76"

- x = pulsar
- + = knots C1, C2 from Lobanov et al

The Inner Knot

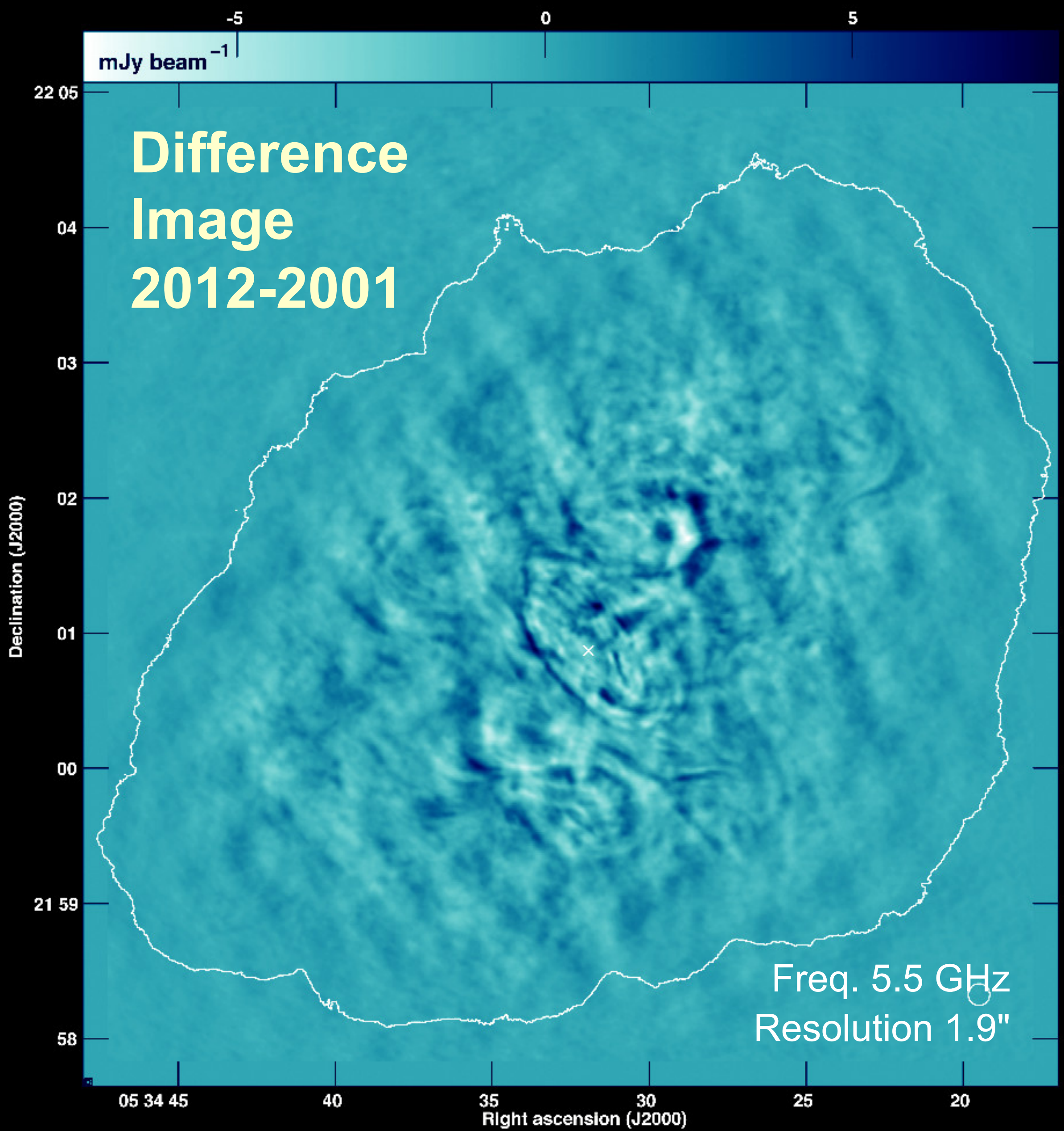
- Inner knot: < 0.3 mJy/beam
- inner knot has a flatter radio→infra-red spectrum than the nebular average ($\alpha = -0.4$
- the inner knot has been associated with a standing shock where the pulsar outflow is deflected by a termination shock (Kommisarov & Lyutikov 2011)



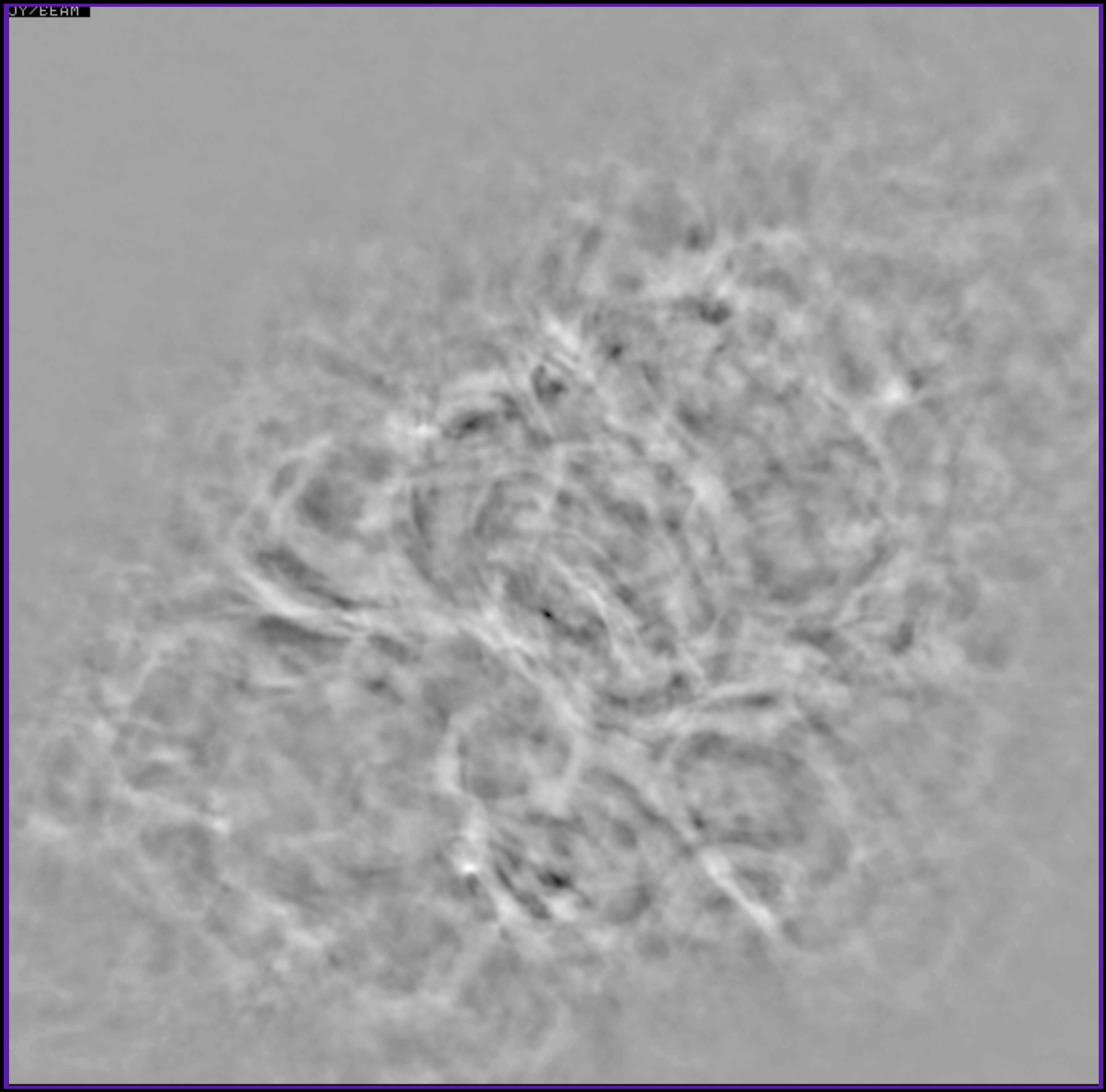
HST image showing features in the inner Crab

Moran et al 2013

- $V L_{\nu}$ at 5.5 GHz of inner knot is only 1.6×10^{-11} that of the spin-down luminosity – surprisingly low radiative efficiency!



- Differences up to 10% of peak brightness
- Timescales longer farther from pulsar
- Consistent with MHD modelling of Olmi et al., 2014, in which the radio morphology reflects the (unstable) underlying flow structure



Longer Term Differences: Expansion

- Images from 1987 and 2012
- High-pass filtered 5-GHz VLA images (B-array only date)

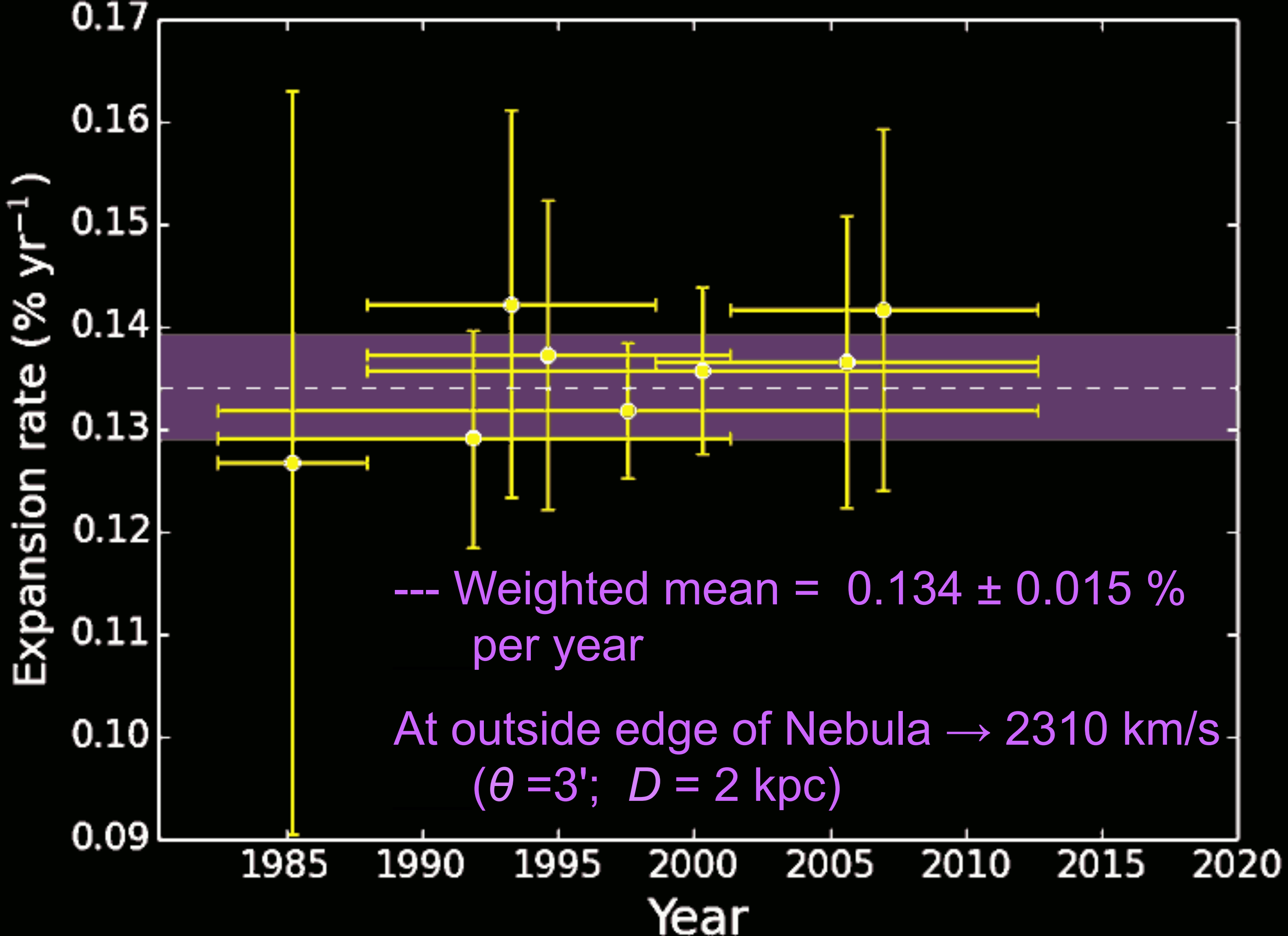
IMDIFF

- Determine the parameters that make one image most closely resemble (least-squares residual) the first image match the second
- Tan and Gull (1985); Sault, Teuben & Wright (1995)
- Free parameters:
  - *e*: spatial scaling
  - *A*: brightness scaling
  - *b*: brightness offset
  - *x,y*: translation
- Maximum interval = 30 yr
- *e* ranges from 1.007 (1982-1987) to 1.040 (1982-2012)

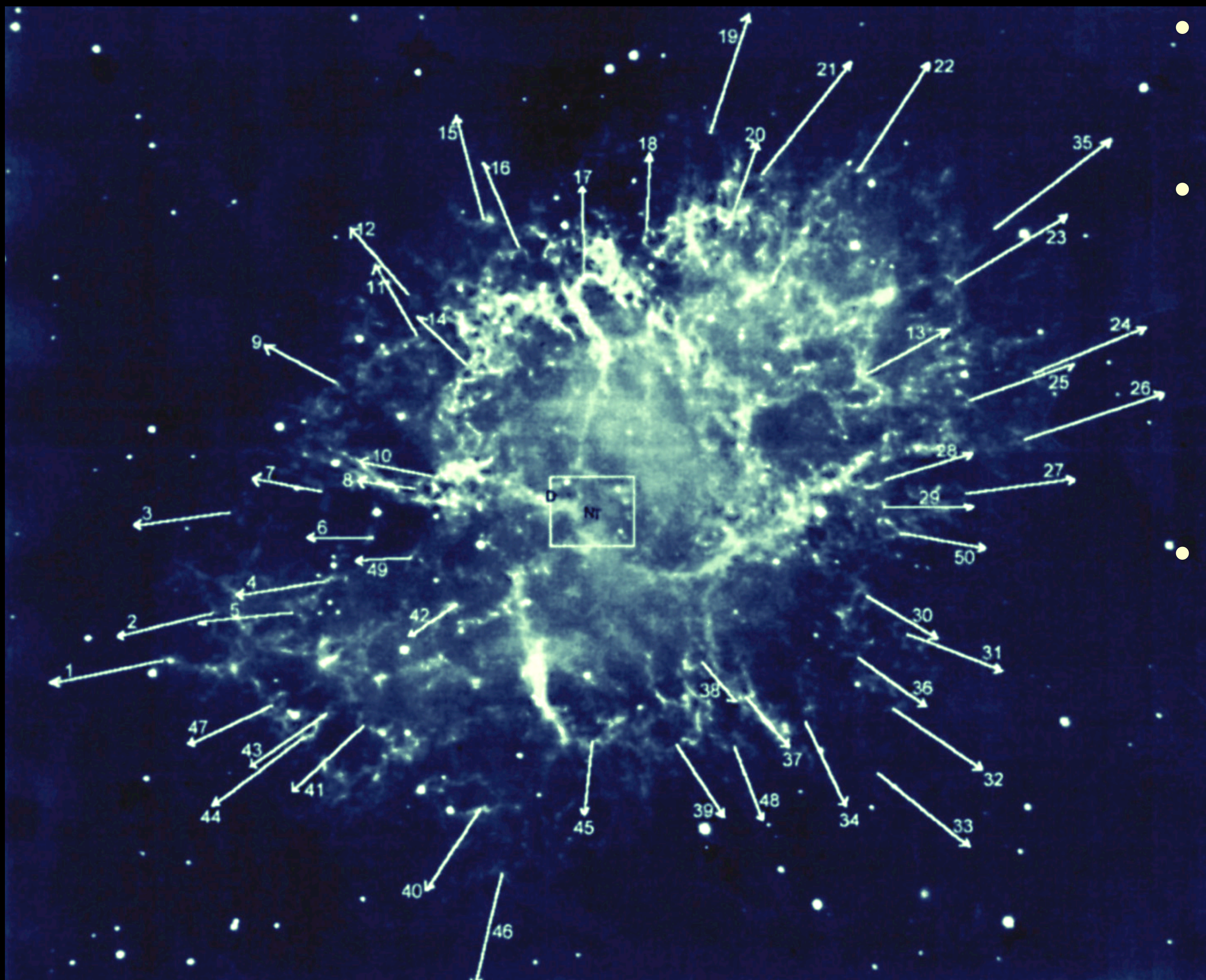
Images
(B-array only)

1982 Apr 24
1987 Dec 29
1998 Aug 09
2001 Apr 17
2012 Aug 26

Expansion in Percent per Year from Radio



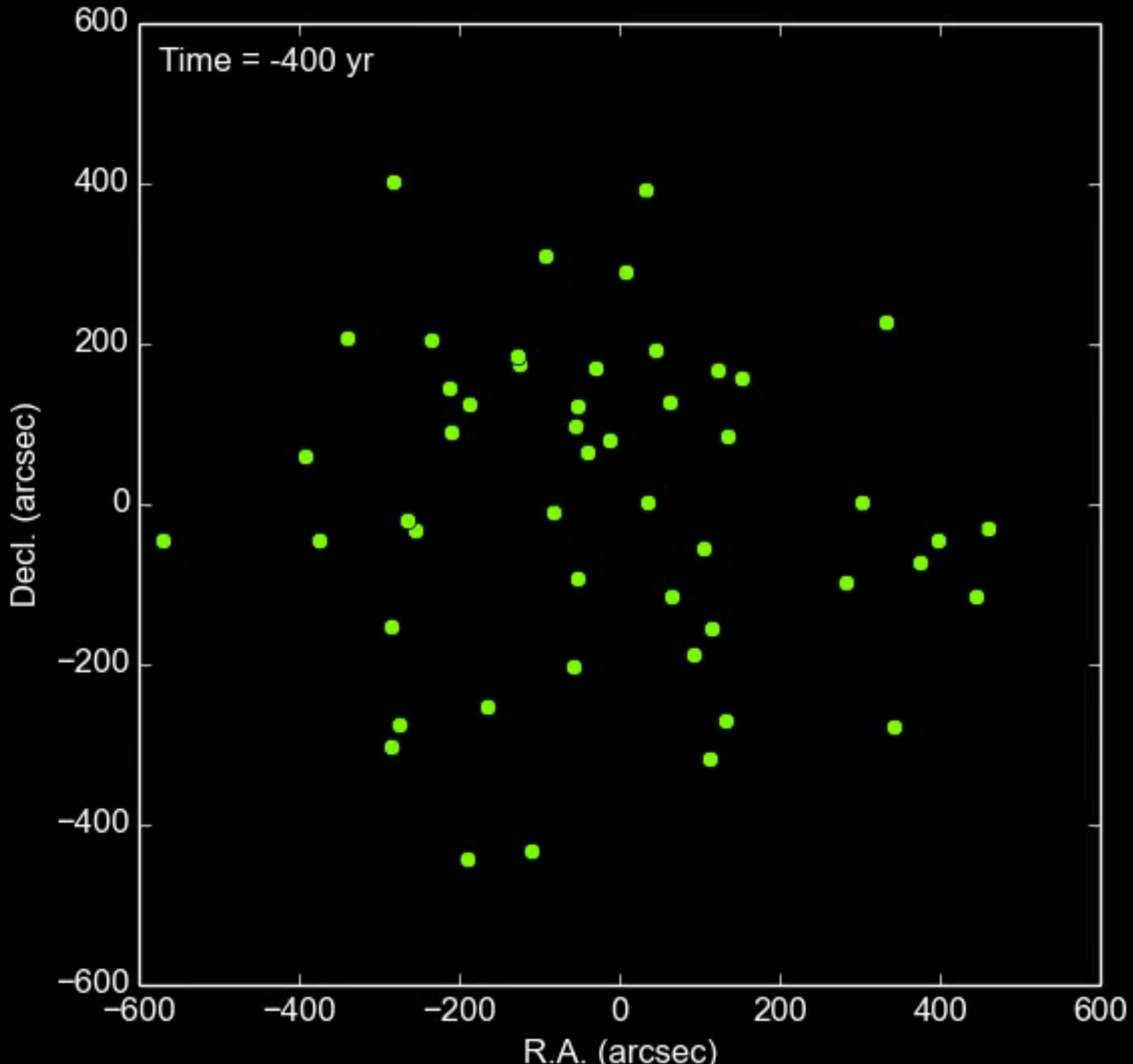
Proper Motions of Optical Filaments



Nugent 1998

- Proper motions of the optical filaments from Nugent 1998
- from four high-resolution images: Baade 1942, Gingerich 1977, Parker 1995, Wainscoat & Kormendy 1997
- "Convergence date" determined by extrapolating measured filament proper motions backwards in time to the time of smallest scatter.

Bias in the Convergence Date



- Imagine a set of measurements of positions and proper motions for a completely static Nebula
- The true "convergence date" would be infinitely far in the past (or future)
- However, errors in the measure-ments of the proper motions will bias the apparent con-vergence date towards the present

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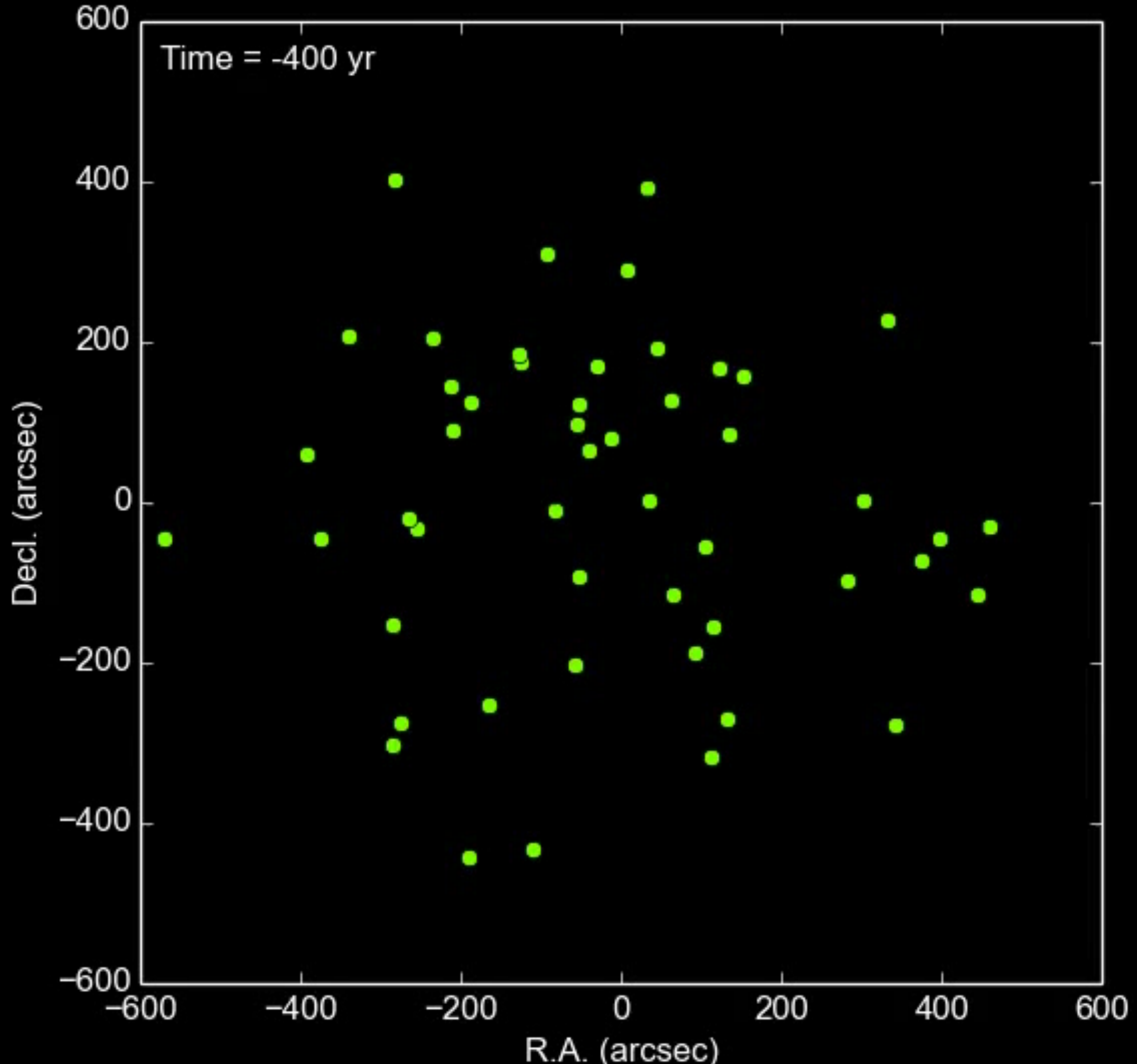

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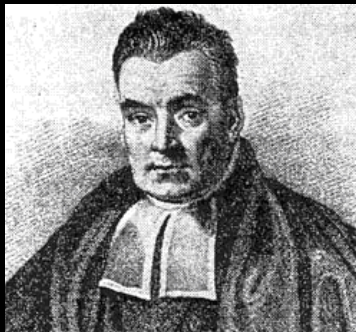


Bayesian Model

Assume starting values:

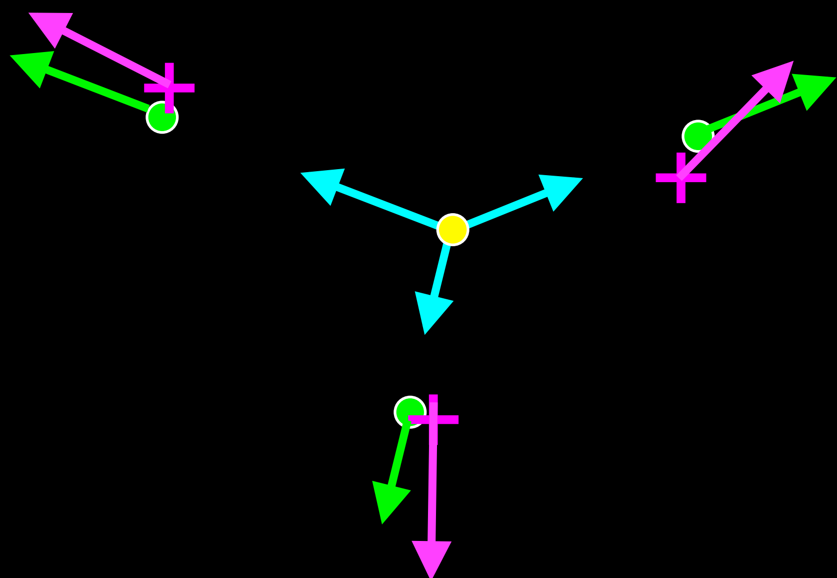
- an origin (convergence point and time)
- a set of (true) velocities

These determine

- the hypothesized actual present day positions and velocities

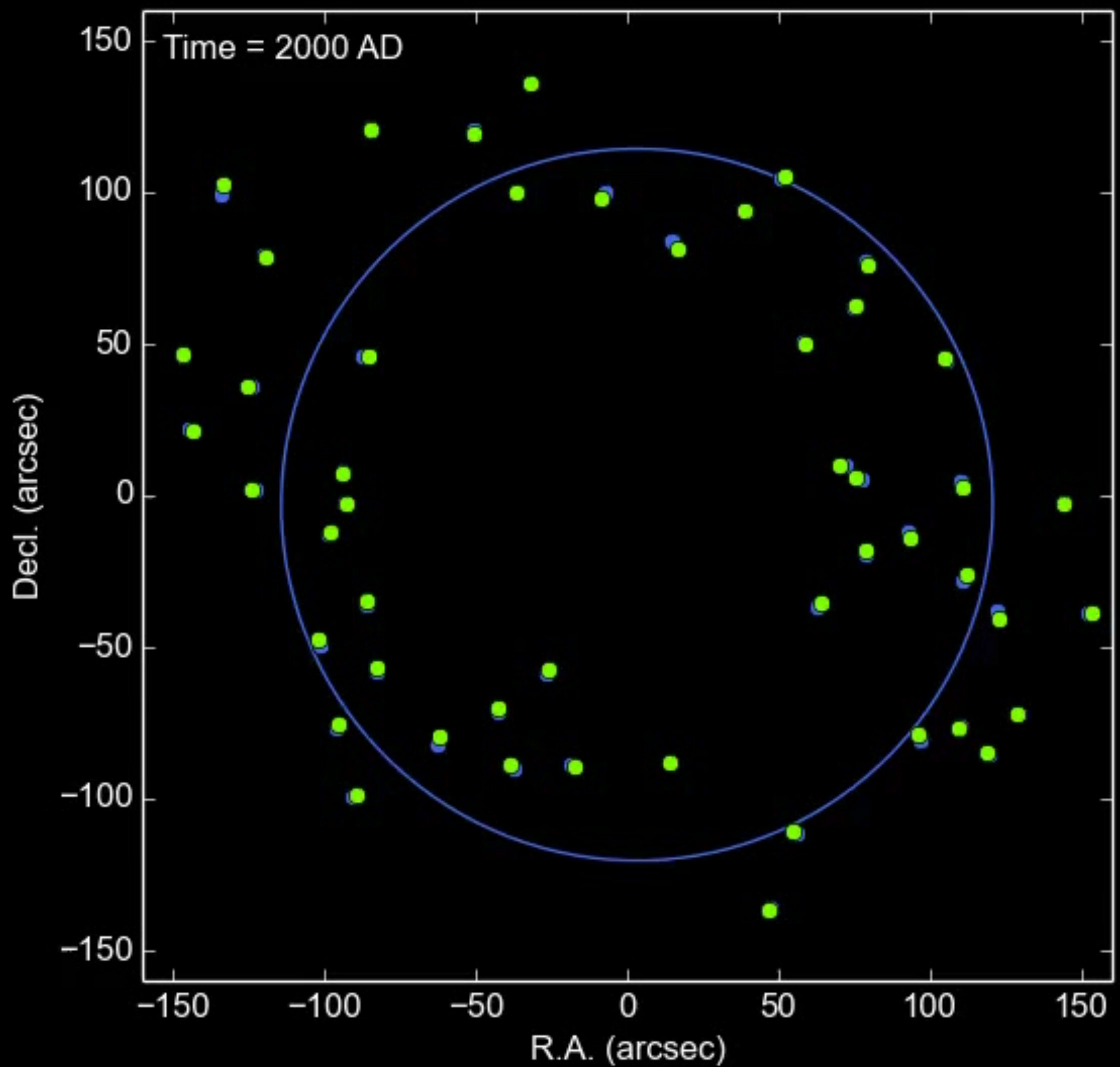
Compare to

- measured positions, with uncertainties
- measured velocities, with uncertainties (not shown)



Then, given the measurement uncertainties, calculate the probability of obtaining the measured values for this set of assumed starting values

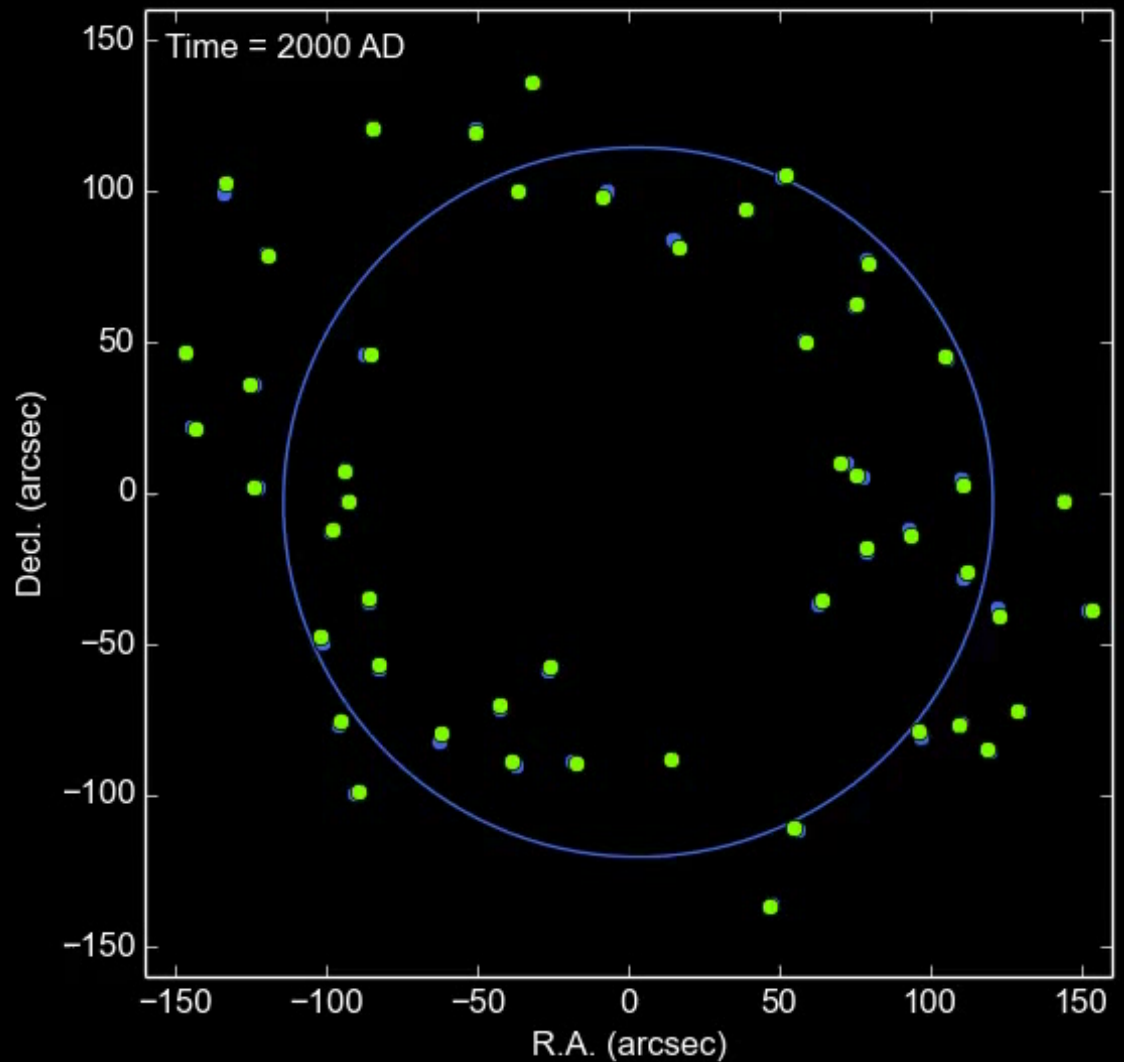
Convergence Date



Measured positions and proper motions

Bayesian estimates of true positions & poper motions

Convergence Date



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Results: Expansion of Optical Filaments

- Convergence date: AD 1091 ± 34
- Convergence position: $5^h\ 34^m\ 33.3^s$, and +22° 00' 42.5" (J2000)
- Estimates not sensitive to choice of prior distribution
- Nugent (1998) got: AD 1130 ± 16 AD. Our uncertainty is higher because we properly account for the uncertainty in the measured proper motions (and positions)

Comparison of Radio and Optical Expansion Rates

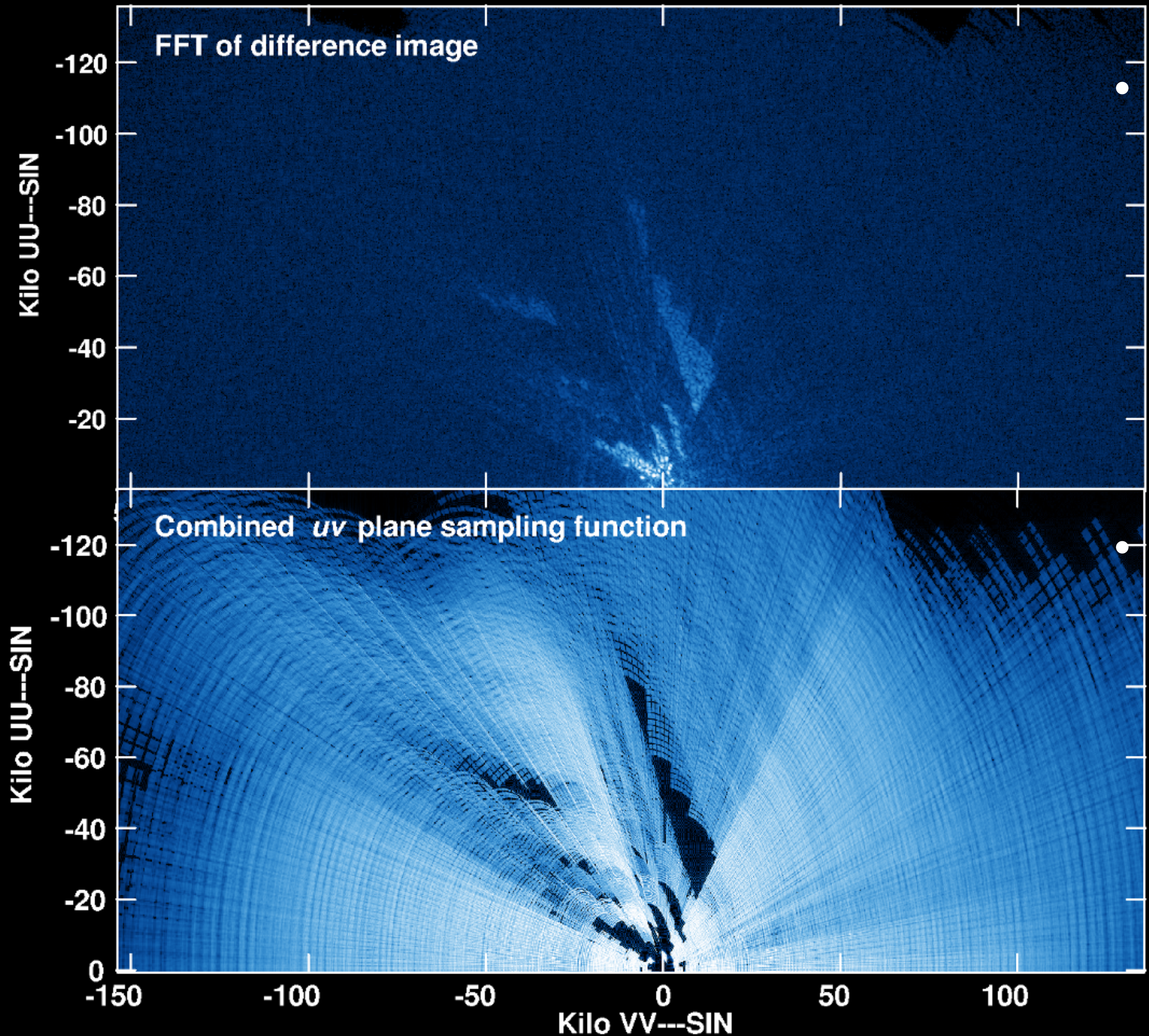
- Optical filament convergence date: AD 1091 ± 34
- Radio synchrotron convergence date: AD 1255 ± 27
- Difference: 164 ± 43 (3.8 σ)
- Radio synchrotron bubble (relativistic fluid) is expanding more quickly than the optical filaments (thermal, massive)
- If we assume power-law expansion for the synchrotron bubble with $r \propto t^m$, starting at 1054.5, then m = 1.26 ± 0.05
- For spherical pulsar wind nebula, expanding into un-shocked (and freely expanding) supernova ejecta, both theory and simulations predict m = 1.1 to 1.3 (Chevalier 1984; Bucciantini et al. 2003, Gaensler & Slane 2006, van der Swaluw et al 2001)
- For the filaments, m = 1.04 ± 0.04

Interpretation: RT-Instability at the Pulsar-wind bubble/ejecta Interface

- The filaments are thought to be formed by the Rayleigh-Taylor instability at the interface between the accelerated pulsar-wind bubble and the freely expanding supernova ejecta (e.g. Chevalier)
- Expect that the synchrotron bubble will push through the filaments – exactly what we see
- Our measurements are not compatible with scenarios were the

Very
Large
Array
λ=6 cm

My
parents



- Fourier transform of diference images
- Combined sampling functions (in the Fourier domain)

Bayesian Approach

- We have measurements (with errors) of the present day positions and proper motions
- Assume that:
  - Filaments originated at some particular point in time and space: convergence time and explosion location
  - that they have moved at constant speed since then
- For any given hypothetical convergence time and position and a set of hypothetical true motions, we can uniquely calculate the present-day positions
- We then compare these hypothetical positions to the measurements, and determine the probability of obtaining the measured values.
- Using Markov-chain Monte-Carlo integration, we integrate over the different hypotheses, and determine the most probable values of the convergence time and position (given the measurements)

Bayesian Approach (Details)

- I took the following prior distributions:
  - Uniform with a range of AD 500 to 1500 for the convergence date
  - Gaussian with σ 200" around the present mean position for the convergence position
  - Gaussian with mean 10" on the present position of the filaments (filament positions very unlikely to be in error by this much). This is equivalent to taking a prior distribution on the true expansion velocities.

Expansion Velocity of the Crab